

Comparative Evaluation of Single- and Multi-Marker Pose Estimation for Freehand 3D Ultrasound Reconstruction

Syahid Al Irfan*, Prima Oky Dicky Ardiansyah*

Presenter : Syahid Al Irfan*
s236x002@s.iwate-pu.ac.jp

*Iwate Prefectural University

■ Profile of the Presenter

Syahid Al Irfan is a PhD student at Iwate Prefectural University and was born in Indonesia. Before continuing his studies in Japan, he had two years of professional experience in the fields of IoT and software engineering.

His PhD research focuses on the development of medical devices, particularly ultrasound technology, intended for early-stage cancer screening.

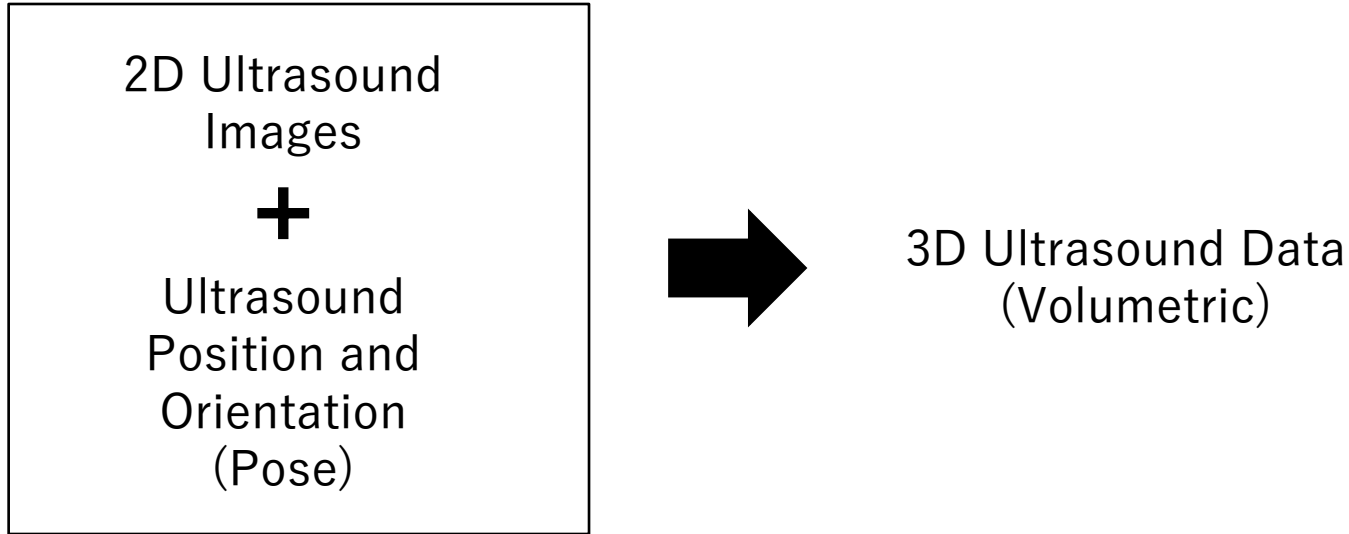
■ What will be presented

- Paper Introduction
- Related works
- Method
- Implementation
- Result

■ Paper Introduction

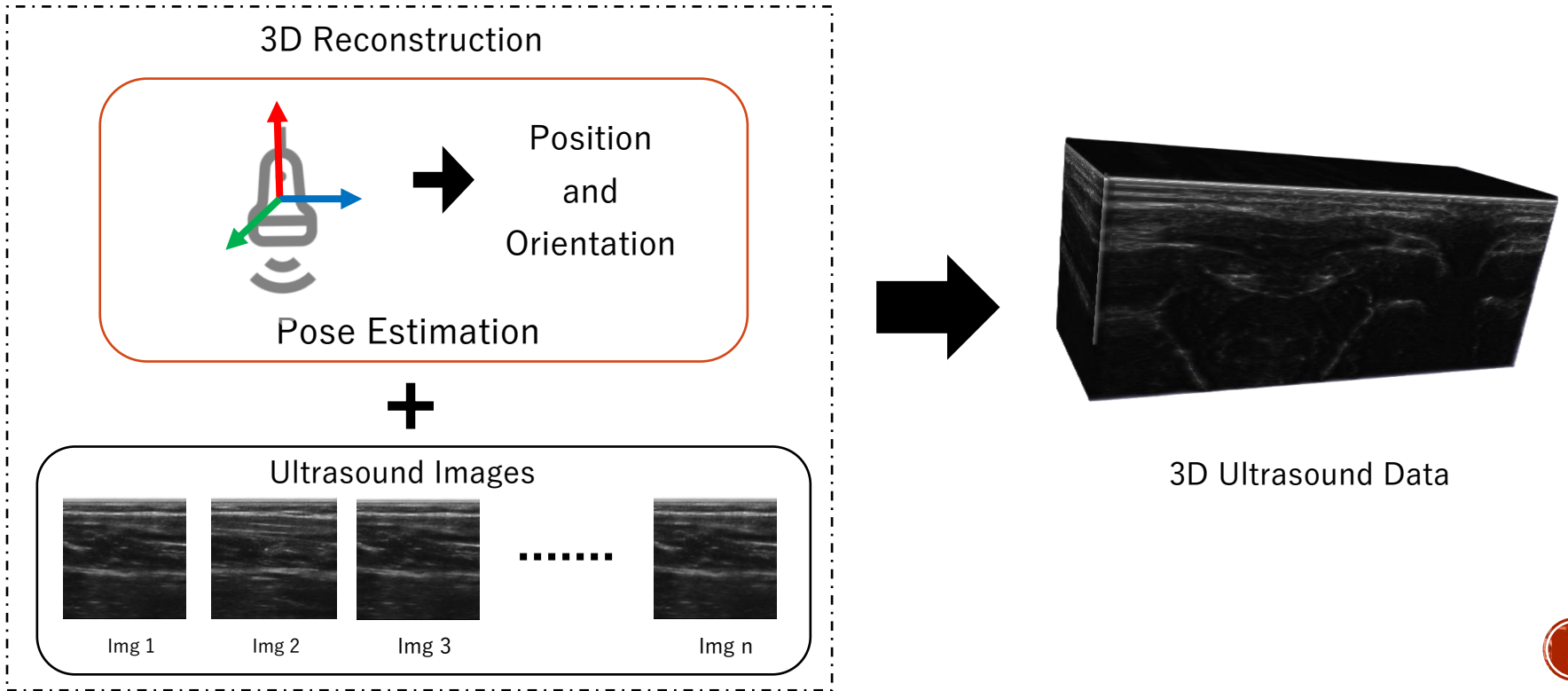
What is 3D Ultrasound?

3D ultrasound is a technique for generating volumetric data by reconstructing a series of 2D ultrasound images together with their corresponding probe position and orientation into a 3D volume.



Paper Introduction

One way to obtain pose data from the probe is by using a computer vision technique, such as pose estimation of the ultrasound probe, and assigning the estimated pose to each ultrasound image



■ Paper Introduction

One pose estimation method that can be used for 3D ultrasound reconstruction is marker-based pose estimation, where visual markers are attached to the probe and tracked to estimate its position and orientation.

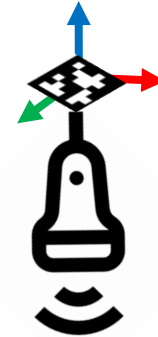
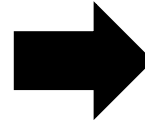


Marker Detection

+



Ultrasound
Probe

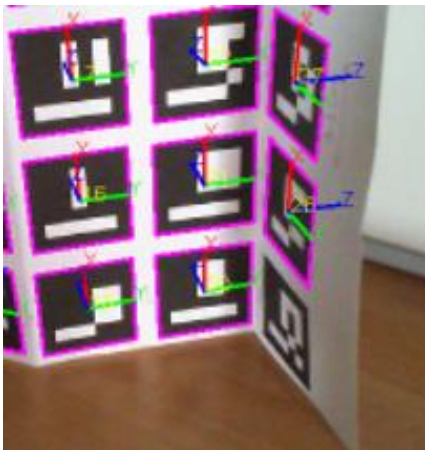


Marker Attached
to Ultrasound

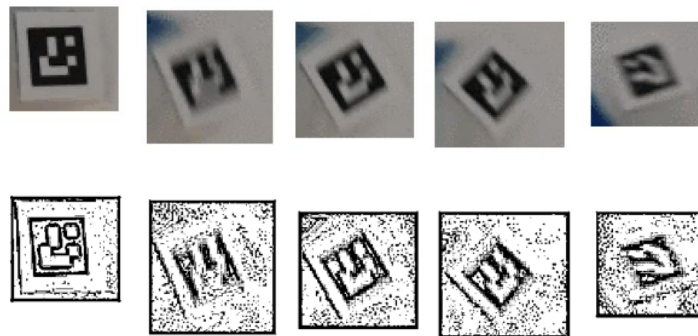
This marker-based pose estimation technology shows strong potential as a compact and simple modular pose estimation method.

Paper Introduction

However, in single marker-based pose estimation processes, several challenges exist such as self occlusion or motion blur which may result in unstable detection and cumulative pose drift during 3D reconstruction.



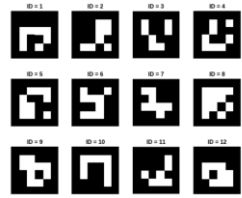
Self Occlusion



Motion Blur

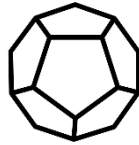
Paper Introduction

One solution to address the problem in single-marker pose estimation is the use of a multi-marker with fiducial configurations by arranging multiple markers on different faces such as dodecahedron shape.

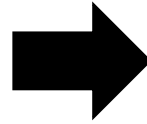


Multi-Marker

+



Dodecahedron
Shape



Dodecahedron Shape Marker

However, using a dodecahedron requires a consistent physical design for each marker.

■ Paper Introduction

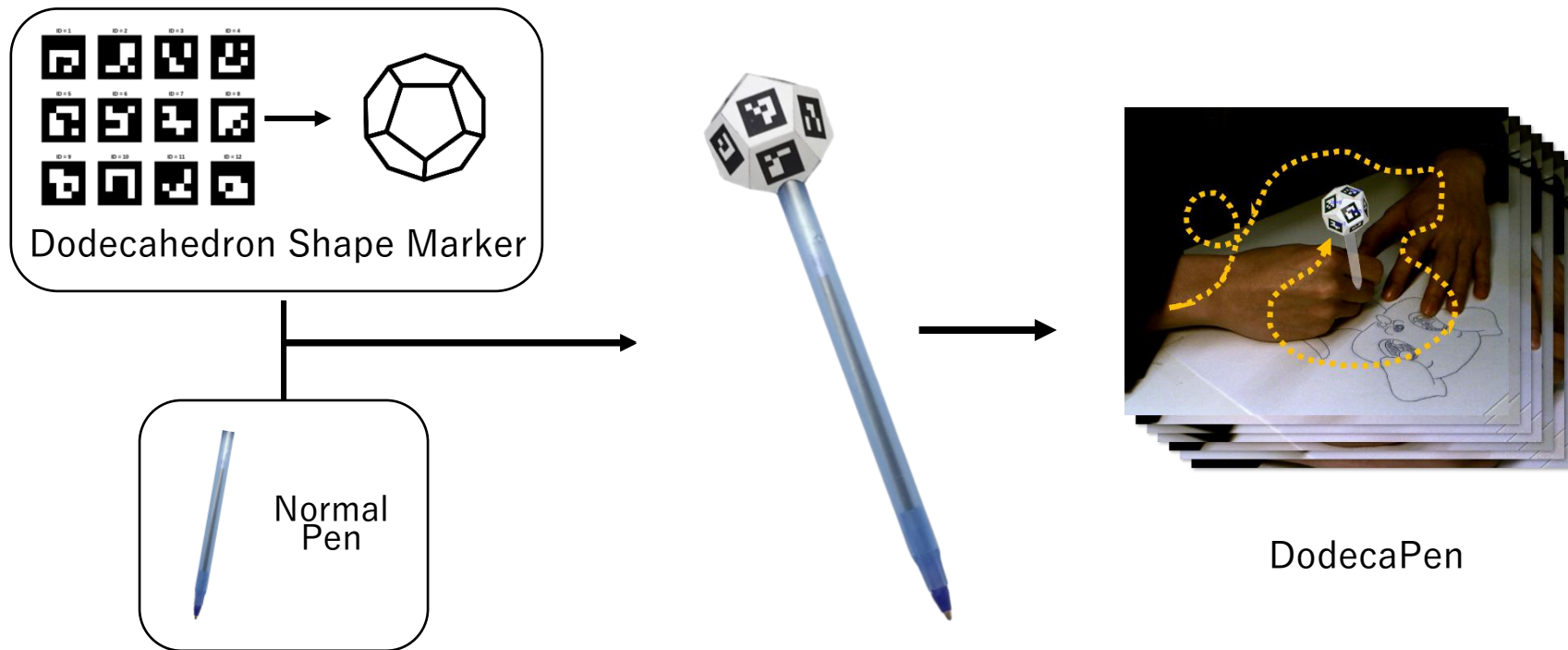
Research Aim

This research aims to evaluate the performance of single-marker and dodecahedron-based pose estimation for 3D ultrasound reconstruction and determine whether there is a significant difference in accuracy between these two methods in the 3D ultrasound reconstruction result.

Related works (1/3)

Title : DodecaPen: Accurate 6DoF Tracking of a Passive Stylus

Method: Uses multiple Aruco markers arranged in a dodecahedron structure and projects the global reference points to the stylus tip position.



■ Related works (1/3)

Title : DodecaPen: Accurate 6DoF Tracking of a Passive Stylus

Result :

The study reports that, under optimal settings, the lowest translation error (vector displacement) achieved was 0.336 mm.



Tracking Process



DodecaPen Tracking



Ground-truth Scan

Limitation :

No comparative evaluation was conducted between multi-marker and single-marker approaches for tip projection

■ Related works (2/3)

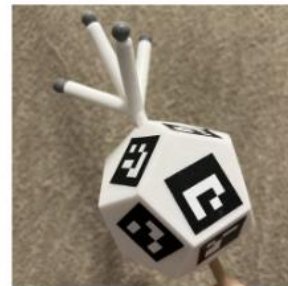
Title: Six-Degree-of-Freedom Freehand 3D Ultrasound: A Low-Cost Computer Vision–Based Approach for Orthopedic Applications

Method: Uses dodecahedron and ARUco markers, with an infrared (IR) tracking system as the ground truth reference.



The marker is placed on top of the ultrasound.

Put Aruco and IR in one cluster



■ Related works (2/3)

Title: Six-Degree-of-Freedom Freehand 3D Ultrasound: A Low-Cost Computer Vision–Based Approach for Orthopedic Applications

Results:



Measurements were performed on the reconstruction results

3D printed Bone inside Phantom

The marker-based pose estimation achieved the lowest average errors (mm) of 0.857, 0.453, and 2.689 along the x, y, and z axes, respectively.

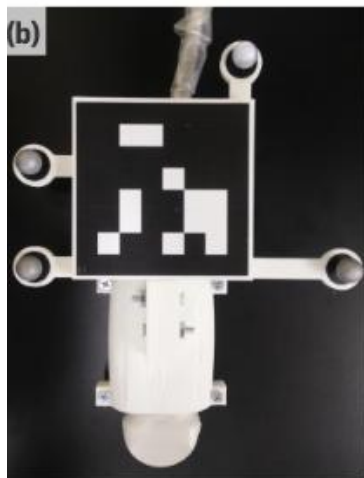
Limitation:

The study did not evaluate reconstruction performance on small objects representing cancer cells.

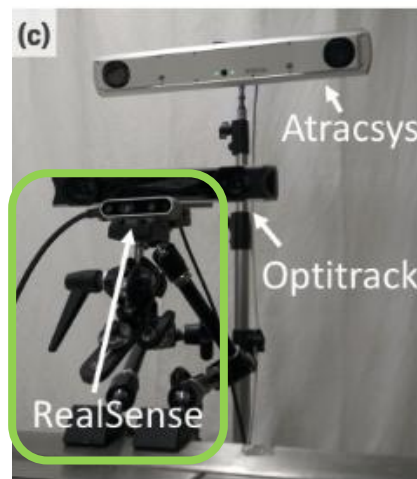
■ Related works (3/3)

Title : Evaluation of Low-Cost Hardware Alternatives for 3D Freehand Ultrasound Reconstruction in Image-Guided Neurosurgery

Method: Uses ARUco markers captured with a RealSense RGB camera and compares the results with other tracking methods.



Use Single marker



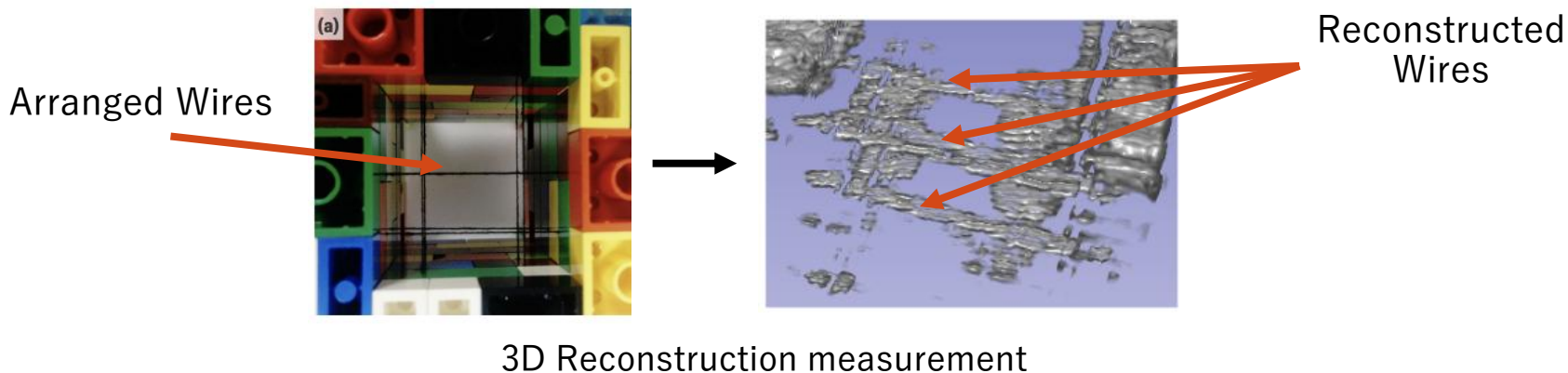
Camera Setup

■ Related works (3/3)

Title : Evaluation of Low-Cost Hardware Alternatives for 3D Freehand Ultrasound Reconstruction in Image-Guided Neurosurgery

Results:

The marker-based pose estimation achieved the lowest average errors of 2.64, 1.50, and 13.83 (mm) along the x, y, and z axes, respectively.



Limitation:

The study also did not evaluate reconstruction performance on small objects representing cancer cells.

■ Method

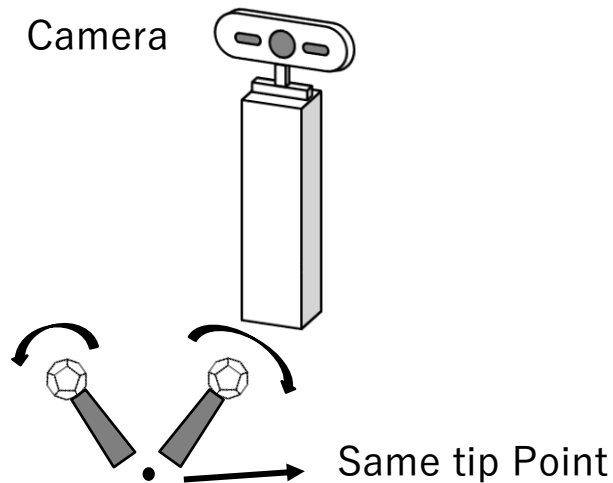
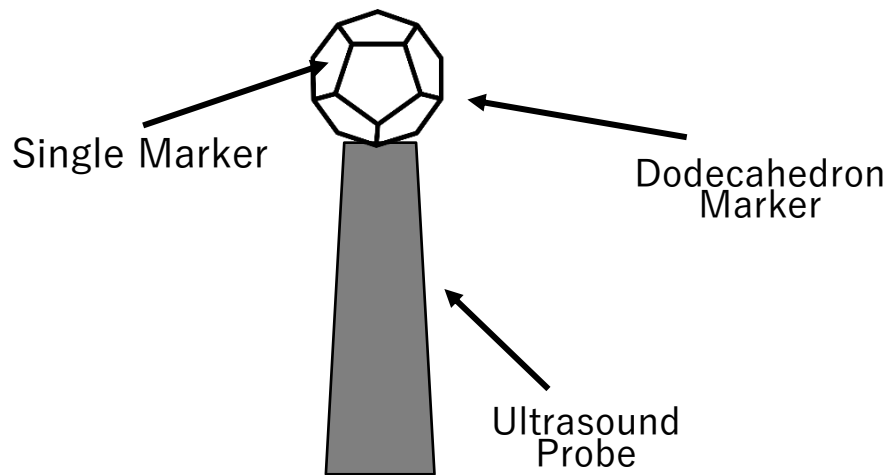
The experimental method is conducted in three stages:

- Calibration testing
- Object measurement using a phantom
- Evaluation

Method

Calibration of Ultrasound Tip Point:

- Multiple markers with a dodecahedron shape were attached to the ultrasound probe.
- A single marker is selected from the set of markers.
- Each marker type is calibrated and tested to ensure that both markers are calibrated to the same probe tip position.

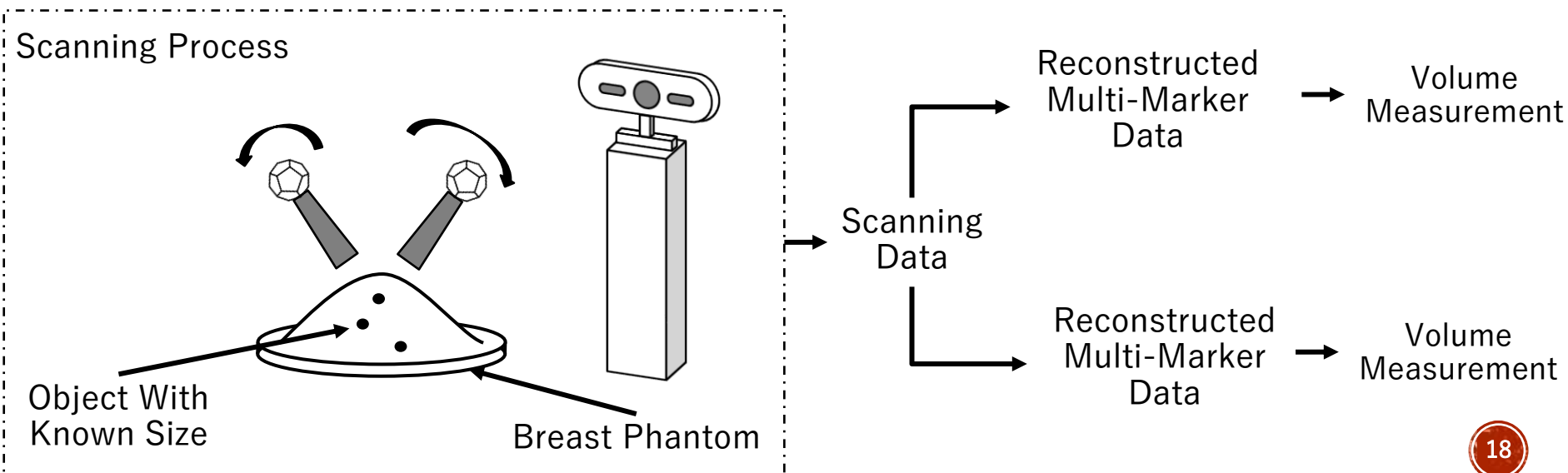


Move randomly, but the tip point remains at the same point

Method

Object Measurement in the Phantom :

- The measurement is performed by scanning a breast phantom (artificial breast) that has multiple objects with a known size inside the phantom.
- From the scanning result, the pose data from both methods and ultrasound images were generated and will be used for 3D reconstruction.
- From the reconstructed data, the volume of each object with a known size was measured.



Method

Evaluation:

- The measurement results are compared with the ground-truth (actual size of each objects).
- An ANOVA statistical test is performed with marker method and object size as variables to determine whether there is a significant difference in accuracy.

Implementation

Dodecahedron shape markers are mounted on the probe (ViewPhii64) at predefined, measured positions.

Environmental parameters such as lighting conditions and camera-to-marker distance are recorded during data acquisition.

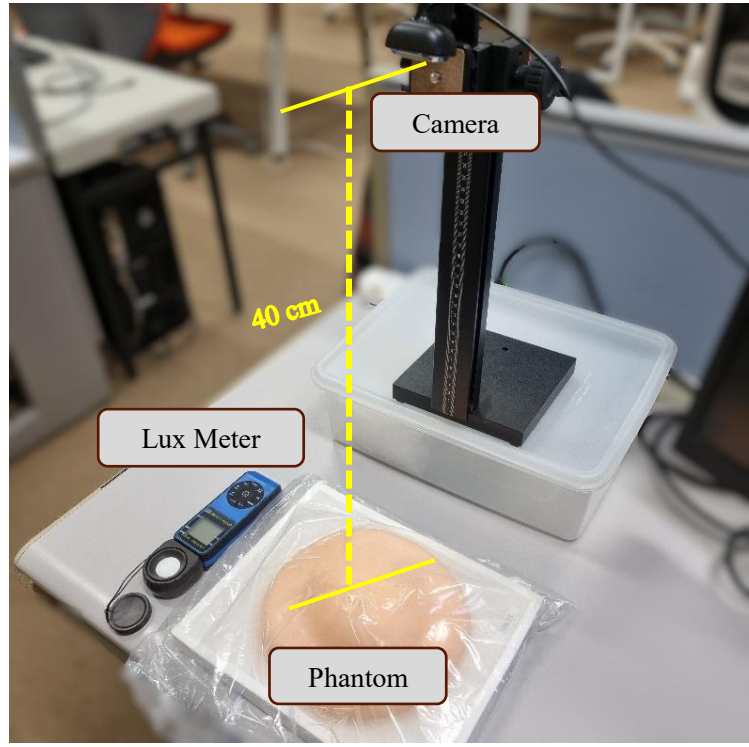
Single Marker



Dodecahedron Marker



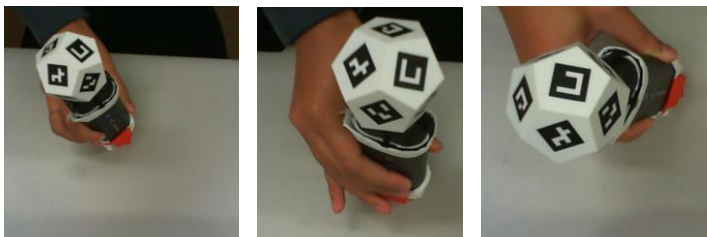
Ultrasound Probe



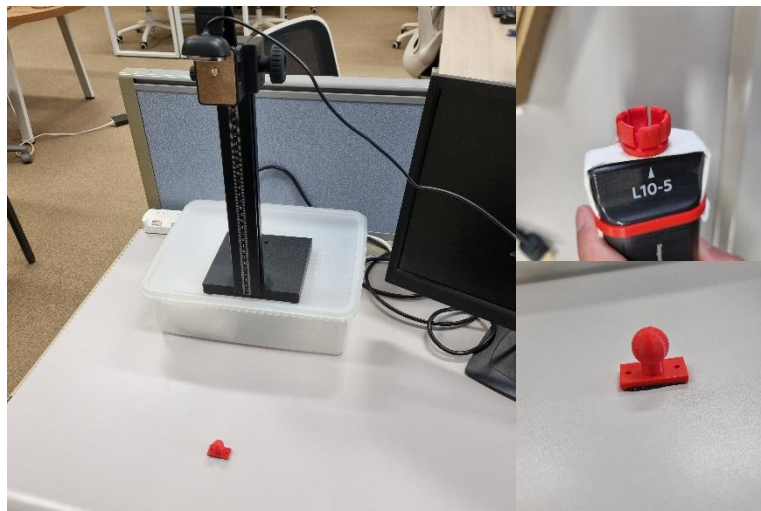
Implementation

Calibration of Ultrasound Tip Point :

The test is conducted by placing the ultrasound probe in the same position, calibrating both markers, and collecting data while the probe moves randomly.



The probe performs random movements while the probe tip remains at the same reference point

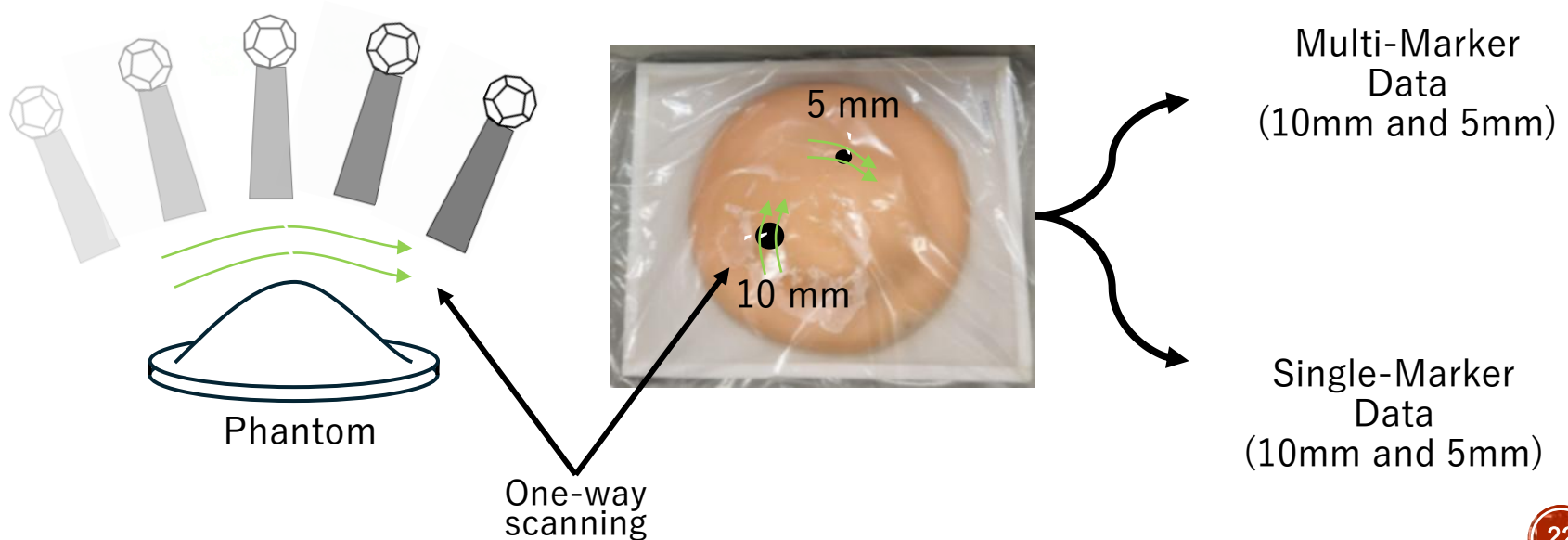


Calibration Setup

Implementation

Object Measurement in the Phantom :

- Scanning is performed in a one-way direction at predefined object locations.
- In this experiment, two objects with sizes of 5 mm and 10 mm were used, and each object was measured ten times.



Calibration of Ultrasound Tip Point :

- Before reconstruction, calibration accuracy was evaluated to ensure both tracking configurations were aligned in the same global coordinate system.
- Under ~ 500 Lux illumination, the average probe-tip projection error was (0.64, 0.02, 0.63) mm for the multi-marker configuration and (0.22, 0.23, 0.91) mm for the single-marker configuration.
- This shows that both marker methods are calibrated at roughly the same tip coordinates.

Result

3D Volumetric Reconstruction Accuracy :

- For a 5 mm object, the multi-marker configuration achieved a lower mean error (12.1 mm³) and reduced variability compared to the single-marker configuration.
- For a 10 mm object, errors increased in both configurations, with the single-marker method showing the highest mean error (132.7 mm³) and greater variability.
- Overall, multi-marker tracking consistently reduced volumetric error and improved reconstruction stability compared to the single-marker approach.

Volumetric Reconstruction Errors

Diameter (mm)	Volume (mm ³)	Error (Measured - Actual)					
		Multi Marker (mm ³)			Single Marker (mm ³)		
		<i>e</i>	<i>Avg</i>	<i>StdDev</i>	<i>e</i>	<i>Avg</i>	<i>StdDev</i>
5	65.5	8.9	12.1	9.7	23	18.5	9.1
		24.9			24		
		15.1			29.4		
		31.3			27.9		
		3.2			20.9		
		7.9			10.8		
		10.1			21.5		
		14.7			19.4		
		0.3			3.7		
		4.7			4.8		
10	523.6	143.2	87.6	29.1	227.6	132.7	56.2
		92.8			223.5		
		59.3			78.9		
		73.3			132.4		
		71.4			85.3		
		69.9			91.6		
		65.2			77.7		
		134.9			148.6		
		92.2			153.5		
		74.2			107.8		

Result

Statistical Analysis :

- Statistical analysis revealed that **object diameter has a highly significant effect** on reconstruction accuracy ($F = 86.02$, $p < 0.001$), meaning that accuracy varies depending on the size of the object measured.
- It was also found that **the marker method has a significant effect** on accuracy ($F = 6.34$, $p = 0.016$), indicating that changing the marker method can result in higher or lower accuracy.
- However, the interaction between these factors reached close to the significance level ($F = 3.57$, $p = 0.067$).

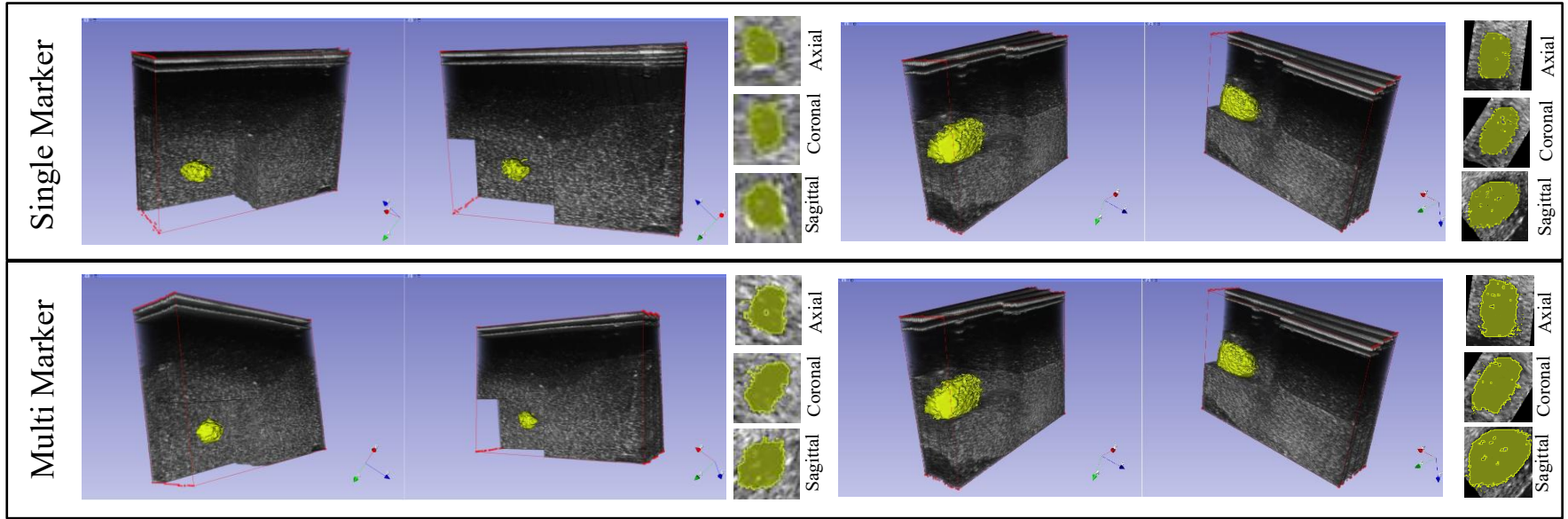
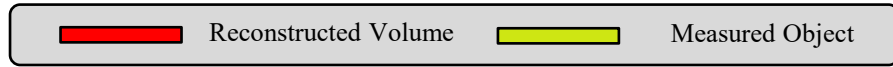
Source	DF	F	p-value
Diameter	1	86.02	<0.001 ***
Method	1	6.34	0.016 *
Diameter × Method	1	3.57	0.067
Error	36	—	—

*, $p < 0.05$, **, $p < 0.01$ (), ***, $p < 0.001$

ANOVA Result

Result

Qualitative Reconstruction Comparison :



Visualization Result

Conclusions

- This study compares single-marker and multi-marker pose estimation methods for freehand 3D ultrasound reconstruction using a controlled breast phantom. Results show that multi-marker tracking significantly improves volumetric accuracy and stability, with the lowest error (12.1 mm³) observed for a 5 mm size.
- Two-way ANOVA confirmed that both object diameter and tracking configuration significantly affect reconstruction error, with multi-marker tracking consistently outperforming single-marker across sizes.